P1.3 NEXRAD-ENHANCED EARLY WARNING SYSTEMS

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1. INTRODUCTION

The Bureau of Reclamation (Reclamation) is designing Early Warning Systems (EWS) for Reclamation and Bureau of Indian Affairs (BIA) dams, to provide enhanced public safety to populations at risk downstream of the dam structures. The EWS designs are comprised of the following components: (1) a method for **detecting** flash-flood events; (2) a **decision making** process; (3) a means of **communicating** warnings between operating personnel and local public safety officials; and (4) a means for local public safety officials to effectively communicate the **warnings** to the public and carry out a successful **evacuation** of the threatened population at risk (Fisher, 1993).

The ability to quickly respond to a heavy rainfall and a potential flash-flood event depends upon adequately detecting the event and transmitting the data to the decision maker in near real time. There is a need to accurately estimate the rainfall water volume in the subbasins of the watershed above the dam. There is a further need for a reliable communications path for transmitting the data or an alert to the decision maker for water management and flash-flood warnings.

The goal behind this research is to develop a methodology, based upon NEXRAD (WSR-88D) radar rainfall estimates, that provides reservoir and river system managers with high-resolution, mean rainfall and water volume estimates (hourly and storm total). This information can be automatically transmitted via a reliable satellite paging system to the decision maker. It is anticipated that in the future, this methodology will be available to enhance EWS at many Reclamation and BIA dam-reservoir-watershed systems throughout the 17 western states. However, such future implementation of the NEXRAD-enhanced EWS will depend upon the radar coverage over mountainous terrain and near real-time data availability.

2. THE AWARDS SYSTEM

Reclamation's initial work on making operational use of NEXRAD rainfall estimates was the development of an automated system to assist water users by providing easy access to rainfall and daily crop water use estimates. The result was the Agricultural WAter Resources Decision Support (AWARDS) system.

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The purpose of the AWARDS system is to improve the efficiency of water management and irrigation scheduling, by providing guidance on when and where to deliver water, and how much to apply.

The AWARDS system is based on modern remote sensing, communication, computer, and Internet technologies. The current AWARDS system works as summarized below and shown in Figure 1.

- NEXRAD Doppler radar systems measure equivalent reflectivity factor (Z_e) data as input to the Precipitation Processing System (PPS). The PPS produces the hourly Digital Precipitation Array (DPA) for each radar system (Level III, Stage I).
- Real-time surface weather stations collect data.
- Radar and weather data are transmitted and input to central computers for processing; the National Weather Service (NWS) River Forecast Centers produce NEXRAD Level III, Stage II and III products.
- AWARDS system computer automatically collects digital format data files of Level III, Stage III radar rainfall estimates, weather station data, and NWS precipitation forecasts, from the central computers.
- AWARDS system computer prepares the rainfall image and chart products, making them available in near real time for Internet access.
- Reservoir operators, water managers, and on-farm water users access the AWARDS system products via the Internet.
- Reservoir operators, water districts' staff and on-farm irrigators make operational decisions based upon the information provided by the AWARDS system.

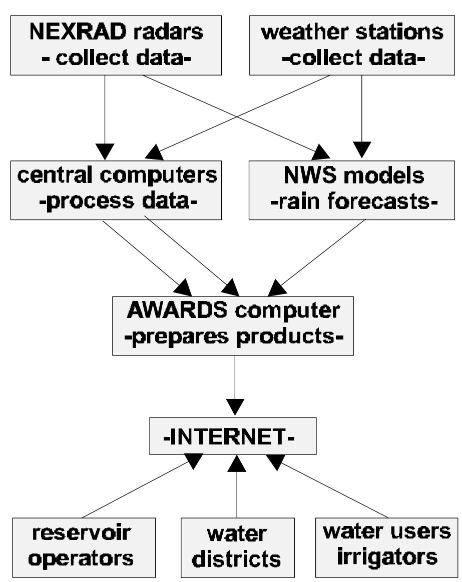

Figure 1. Schematic of AWARDS system.

The AWARDS system automatically integrates 1-hr and 24-hr NEXRAD rainfall estimates --

with 24-hr surface weather station data:

- mean temperature
- mean relative humidity
- mean wind speed
- point rainfall accumulation
- total solar radiation

and uses the NEXRAD radar rainfall estimates and surface weather station data with:

- crop evapotranspiration (ET) equations
- local terrain and soil information
- effective rainfall estimation procedures
- local daily maximum and minimum normals
- quantitative precipitation forecasts (QPF)
- watershed/reservoir systems
- irrigation water distribution systems

to provide the water managers and users with:

- NEXRAD rainfall and watershed rainfall water volume estimates
- effective rainfall estimates
- ET estimates for determining crop water use requirements.

The above information is available from Reclamation's NEXRAD Web page http://www.usbr.gov/rsmg/nexrad.

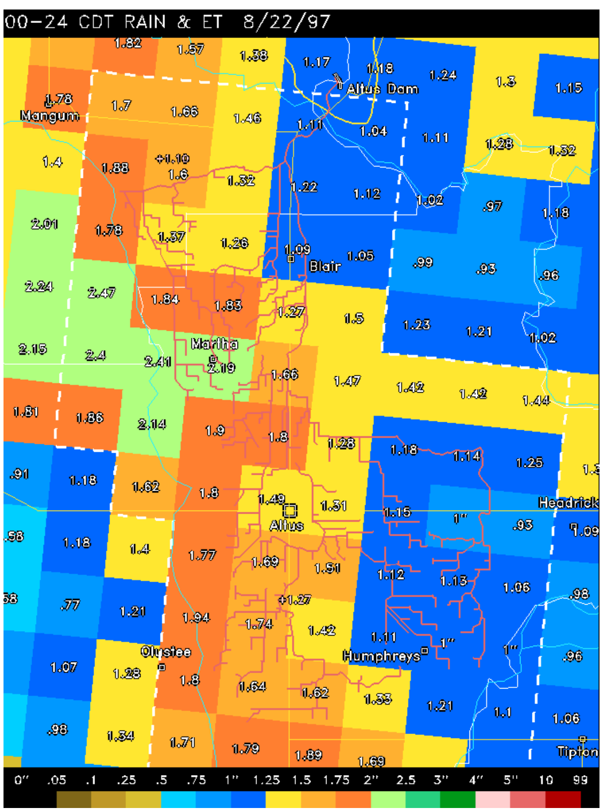

Figure 2. Example of interactive image showing 24-hr NEXRAD STAGE III rainfall estimates.

Figure 2 is an example of an interactive AWARDS system image for the Lugert-Altus Irrigation District, southwestern Oklahoma. The NEXRAD Hydrologic Rainfall Analysis Project (HRAP) grid cells (about 4 X 4 km) in Figure 2 show the estimated 24-hr (midnight to midnight local time) average rainfall (in) for each cell. Also shown (at + signs) are the locations of two Oklahoma Mesonet weather stations (Crawford et al. 1992). The irrigators can click a computer mouse on the HRAP grid cells within the dashed line boundary for pop-up estimated Crop Water Use (ET) charts, and can click on the weather stations for pop-up Daily Weather charts. Examples of these two types of charts are shown in Figures 3 and 4 respectively.

Crop	Start Date	Daily Crop Water Use (In) Penman ET - Aug				Fore-cast Aug	Cover Date	Term Date	Sum ET	7 Day Use	14 Day Use
		19	20	21	22	23					
Cotton	501	0.30	0.29	0.28	0.31	0.28	801	1001	13.1	2.1	3.9
Cotton	507	0.30	0.29	0.28	0.32	0.29	805	1001	12.8	2.1	4.0
Cotton	514	0.30	0.29	0.28	0.32	0.29	810	1001	12.3	2.1	4.0
Cotton	521	0.30	0.29	0.28	0.32	0.29	815	1001	11.3	2.1	3.9
Cotton	528	0.30	0.29	0.28	0.32	0.29	820	1001	10.2	2.1	3.9
NEXRAD Hrs Avail		24	24	24	24	QPF					
Total Rain		0.18	0.00	0.00	1.88	0.00					
Effective Rain		0.18	0.00	0.00	1.69	0.00					
NEXRAD Monthly Total Rain:											
May	3.52										
June	4.67										
July	4.20										
August	9.41										

Figure 3. Example of a pop-up estimated 24-hour Crop Water Use chart, that includes NEXRAD rainfall, effective rainfall, and QPF.

	Aug 19	Aug 20	Aug 21	Aug 22
Max. Temp. (F)	93.7	92.7	91.0	88.0
Min. Temp. (F)	72.3	69.8	69.8	66.4
Avg. Wind (Mi/Hr)	3.1	3.4	3.1	5.1
Rel. Humidity (%)	76.2	77.3	75.9	77.5
Rain (in)	0.17	0.00	0.01	1.10
Solar Rad. (Langleys)	592	555	591	592

Figure 4. Example of a pop-up surface weather station Daily Weather Data chart (from the Oklahoma Mesonet). The data period is midnight to midnight local time.

Similar to the AWARDS system application, use of near real-time (< one hour) NEXRAD data to estimate rainfall over watersheds should enhance existing reservoir and dam EWS, defined in the first paragraph of the paper. NEXRAD should be able to pinpoint the cores of heavy convective storms. The hourly DPA data are available about 45 minutes past each sampled hour. Such data should, in most cases, provide alerts before the runoff is measured by a stream gage. The increased accuracy, reliability, and alert lead time from incorporating NEXRAD rainfall data can provide enhanced public safety to populations downstream of dam structures, reducing the risk of loss of property and life.

3. NEXRAD-ENHANCED EWS DEVELOPMENT AREA

The watershed/reservoir/dam system selected for initial development of a NEXRAD-enhanced EWS was above Olympus Dam and Lake Estes near Estes Park, CO. The Olympus Dam EWS is an excellent example of the type of surface EWS that Reclamation is in the process of installing. The watershed above Olympus Dam covers a limited area of about 400 km^2. The EWS hardware consists of 11 stations with multiple sensors, including 10 precipitation gages, 9 stream gages, 2 reservoir level sensors, and 4 temperature sensors. Two of the stations also measure wind speed and direction, atmospheric pressure, relative humidity, and fuel moisture. There is also a pressure transducer at Olympus Dam. These monitoring stations transmit data via line-of-site VHF radio to a repeater site (PMRS+) which splits off a microwave signal that is placed into Reclamation's Eastern Colorado Area Office microwave system. The data are received at three independent EWS base stations, located at the Eastern Colorado Area Office (microwave), the Estes Power Plant (VHF), and the Reclamation - Western Area Power Administration (WAPA) Joint Operations Center (microwave and VHF). All of the Olympus Dam EWS monitoring stations and the radio repeater site are listed in Table 1 and shown in Figure 5.

Table 1. Olympus Dam Early Warning System Sites

Site ID -- Name	Elev. (m)
BCWP – Black Canyon Water Plant	2440
FREP – Fall River Endovalley Picnic	2650
CCEP – Chiquita Creek Endovalley Picnic	2650
FRCD – Fall River Cascade Dam	2590
HVSA – Hidden Valley Ski Area	2865
BTMP – Big Thompson Moraine Park	2465
BTPP – Big Thompson Power Plant	2285
FCGC – Fish Creek Golf Course	2300
BTEP – Big Thompson East Portal	2375
GCSL – Glacier Creek Sprague Lake	2660
LLDS – Lily Lake Dump Site	2745
ODPT – Olympus Dam Pressure Transducer	2285
PMRS – Prospect Mountain Repeater Site	2715

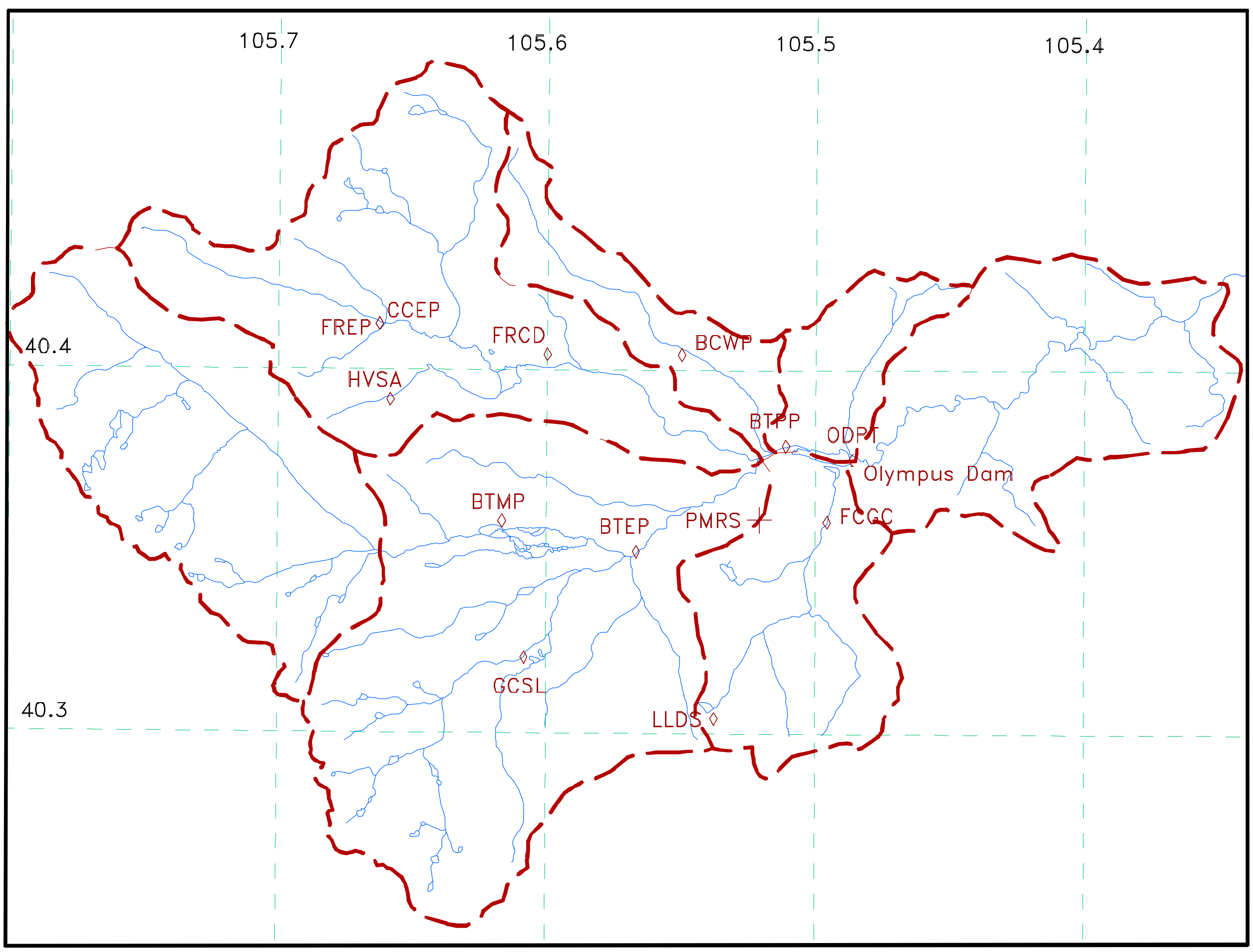

Figure 5. Olympus Dam watershed near Estes Park, CO, showing the EWS stations listed in Table 1. The dark long broken lines show the boundaries of the watershed and the subbasins within the watershed. The dashed lines are north latitude and west longitude at 0.1° intervals as shown in the figure.

4. NEXRAD-ENHANCED EWS PROCEDURES

Requirements for the NEXRAD-enhanced EWS for the Olympus Dam watershed include the following:

- Obtaining NEXRAD STAGE III hourly DPA data files automatically via ftp from the NWS Missouri Basin River Forecast Center.
- Obtaining hourly rainfall accumulations, in a digital format, from the 10 EWS tipping-bucket rain gages automatically from one of the three base stations.
- Development of a computer program that runs on a Sun UNIX computer workstation, automatically retrieving and processing NEXRAD and EWS rainfall data each hour.
- Coordination with the Olympus Dam EWS alert decision makers to establish critical rainfall values for the entire watershed and each subbasin.
- Development of a computer program to calculate each hour the storm total cumulative rainfall and hourly mean rain water volume for the entire watershed and each subbasin.
- Development of a procedure for the Sun Workstation to automatically send scripted e-mail alerts via a reliable satellite paging system.
- Development of a program for the Sun Workstation to prepare the rainfall image and chart products, and to make them available in near real time for Internet access.

These components of the NEXRAD-enhanced EWS for the Olympus Dam watershed are discussed in more detail in the following subsections.

4.1 NEXRAD Rainfall Data

The Olympus Dam watershed is within view of both the Denver and Cheyenne WSR-88D radars. The Denver (or Front Range) WSR-88D radar is located about 105 km SE of the watershed, and the Cheyenne radar is located about 110 km NE of the watershed. At these ranges, the radar beam for the lowest-available 0.5° tilt angle is less than 50% blocked from both radars. Thus a predetermined dBZ value is added by the PPS algorithm to each sample volume that is partially blocked. Both the Denver and Cheyenne radars should provide good rainfall estimates over the Olympus Dam watershed. Therefore, the following actions have been taken:

- Arrangements have been made with the Missouri Basin River Forecast Center to automatically ftp NEXRAD Level III, Stage III digital precipitation data to Reclamation's Technical Service Center about 45 minutes after the end of each sampled hour.

- A UNIX computer program has been developed to display the hourly and storm cumulative NEXRAD rainfall estimates on the HRAP grid, and to calculate rain water volume over subbasins of the Olympus Dam watershed each hour.

4.2 EWS Rainfall Data

The installation of the 10 tipping-bucket rain gages was completed during the summer of 1997. The gages include NovaLynx Model 2500 (heated) and NovaLynx Model 2501 (non-heated) tipping bucket gages. All of the gages are non-shielded and have 8 in. orifices. Since flash floods are not a problem during the winter season, all-season gages were installed at only 2 of the 10 sites. It is anticipated that these 10 tipping-bucket rain gages within the watershed can be used for comparison with the NEXRAD rainfall estimates. Also, they will continue to be used as designed for the current EWS (without NEXRAD rainfall estimates). This will permit comparisons to be made between the two rainfall estimating techniques.

4.3 EWS Automatic Alerts

Getting the heavy rainfall alerts to the EWS decision makers quickly is just as critical as making near real-time rainfall estimates over the watershed. The method for doing this is the combined use of computer and satellite paging system technologies. Whenever the computer program detects that the hourly or cumulative rainfall exceeds predefined limits, the program will prepare a scripted e-mail alert, which will be sent out immediately via a satellite paging system. The following tasks are scheduled for completion during the fall of 1997.

- Coordination with Olympus Dam EWS decision makers to establish critical warning values for each subbasin within the watershed.

- Development of a procedure to automatically send scripted e-mail alerts via a highly reliable satellite paging system.

Testing of the NEXRAD-enhanced EWS for the Olympus Dam watershed is planned for the summer of 1998. These tests will include storm case study comparisons of EWS station rain gage measurements with NEXRAD Level III, Stage III rainfall estimates.

5. NIDS PRODUCTS FOR EWS RAIN ESTIMATION

The NEXRAD rainfall estimates presently used with the AWARDS system, and with the developing NEXRAD enhanced EWS system for the Olympus Dam watershed, are the merged Level III, Stage II hourly DPA files, which are called Stage III. Special arrangements have been made to receive these digital data files via automatic ftp from a number of NWS River Forecast Centers. As previously noted, these files arrive by about 45 minutes after the end of each sampled hour. These digital data files use the Hydrologic Rainfall Analysis Project (HRAP) grid (Greene and Hudlow, 1982) which has a spatial resolution of about 4.0 X 4.0 km in Oklahoma. However, the HRAP grid cell size increases with latitude, e.g., grid cell length is 4.36 km at 45° latitude.

The Stage III hourly DPA has a high-resolution accumulation (A), using 256 data levels with logarithmic

0.125 dBA intervals. The HRAP grid cell size seems to be sufficient for the AWARDS system. However, it is not clear whether the 45 minute delay in receiving the previous hour's data, and the approximate 4 X 4 km spatial resolution, will be adequate for EWS use. If not, how can the temporal and/or spatial resolutions be improved, and what are the tradeoffs? Another consideration when using Stage III is that there can be a problem with the data in areas of overlapping WSR-88D 230 km range umbrella coverage. Currently, Stage II precipitation fields are mosaiced or merged by averaging non-zero precipitation accumulations to generate the Stage III analysis. Pereira et al. (1996) showed that wherever WSR-88D surveillance areas overlap, analysis errors induced by the radar-range effect alone adversely affect the merging.

In addition to using Stage III data obtained by special arrangements with NWS River Forecast Centers, two other basic approaches exist for providing near real-time NEXRAD estimation of rainfall over Reclamation and BIA EWS watersheds. Each of these approaches should reduce the Stage III 45-min delay between the sampled hour and receipt of rain estimates. One approach would use NEXRAD Information Dissemination Service (NIDS) rainfall products provided by the standard NEXRAD Precipitation Processing Subsystem (PPS) algorithm. The other approach would use NEXRAD observations of Z_e as input to a separate precipitation algorithm. Some potential advantages and drawbacks of both approaches will be discussed.

5.1 NIDS Rainfall Products

The EWS should obtain rainfall estimates as soon as practical after the fact to provide warnings as soon as possible. Consequently, the usefulness of NIDS products should be evaluated because they are available in near real time. Klazura and Imy (1993) discuss the several NIDS products, and note that, with the exception of the three NEXRAD agencies, private organizations and government agencies will usually not have real-time direct access to WSR-88D data. That is, the NEXRAD system is designed so that almost all non-NEXRAD agency users are expected to use NIDS vendors for obtaining near real-time products.

NIDS precipitation products include hourly accumulations from the PPS algorithm. A number of limitations exist with the PPS which will not be discussed here. Hunter (1996) provides a good discussion of NEXRAD, the PPS, and associated problems with radar rainfall estimation.

The two potentially most useful PPS NIDS products for the EWS are the one-hour DPA and the one-hour precipitation (OHP), the latter intended for graphical displays. The DPA has been noted to have high accumulation resolution. However, the DPA spatial resolution is about a 4 km X 4 km for the HRAP grid, or 16 km^2 per grid cell. That resolution is rather course for small watersheds like that above Olympus Dam (about 400 km^2) where 25 cells are equivalent to the entire watershed's area.

The graphical OHP product has better spatial resolution with a 2 km X 1° polar grid, and it could be decoded into digital form. But this product has only 16 levels (instead of 256) so the hourly accumulation resolution would be limited. It would be useful to compare DPA and OHP products with rain gage data over small watersheds typical of those that have flash-flood potential. Such comparisons with real radar and gage observations should reveal the better PPS NIDS product for EWS use.

5.2 NIDS Reflectivity Data

The other approach would be to obtain NIDS reflectivity data in near real time and input these measurements into a separate precipitation algorithm. The highest resolution Z_e data recorded are called Level II, with 0.5 dBZ intervals and single range bin (1° X 1 km) spatial resolution. Level II data are used as input to the PPS algorithm calculations associated with each WSR-88D. However, Level II observations are rarely available to non-NEXRAD agency users in real time.

Level III reflectivity data are a NIDS product available for the four lowest radar antenna tilts soon after each volume scan in the same range bin spatial resolution as Level II data (1° X 1 km). But Level III Z_e observations are "degraded" to 5.0 dBZ resolution in precipitation scanning mode (4.0 dBZ in clear air mode). The lower reflectivity resolution is presumably because the Level III reflectivity product is intended to be graphically displayed with up to 16 levels of color. More levels (colors) would be difficult to interpret.

Reclamation has recently developed the means to use Level III reflectivities as input to a snow algorithm. Reclamation meteorologists and programmers began development of a Snow Accumulation Algorithm (SAA) for the NEXRAD Operational Support Facility in June 1995. The ongoing SAA development was described in detail by Super and Holroyd (1996, 1997a) and an overview was presented by Super and Holroyd (1997b).

The SAA was tested in real time during the 1996-97 winter at the Cleveland and Minneapolis National Weather Service Forecast Offices where Level II reflectivities were available as input. Reasonable results were obtained as discussed by Naistat et al. (1998) for the Minneapolis region. But Reclamation will not have Level II data available, so the SAA has been modified to use Level III reflectivites decoded from the 16 level graphical product. Further testing is needed but initial SAA runs with both Level II and Level III data for Minnesota snow storms indicates quite reasonable agreement. That is, degrading the Z_e measurements from 0.5 to 5.0 dBZ resolution does not appear to result in serious degradation of snow water equivalent estimation over several hours. Similar tests should be made with rain over shorter intervals to determine whether Level III reflectivity observations are adequate for use with EWS.

The SAA can easily be modified into a rain algorithm by changing the Z_e-R relationship (where *R* is precipitation rate) into one appropriate for rain in the region of interest, and making a few other adjustments. The SAA is constructed so that "hybrid scans" are customized for individual radars based on data for a few snow storms. These SAA hybrid scans can later be easily modified if noticeable ground clutter frequently appears at particular range bin locations. The NEXRAD PPS also uses a customized hybrid scan at each WSR-88D, based on calculations of standard refraction beam height relative to terrain elevation files. The PPS attempts to locate the beam center closest to 1000 m above the radar, while ensuring that the calculated beam bottom is at least 150 m above local terrain and any beam blockage closer to the radar is less than 50 percent for the particular radial. For flat terrain the PPS hybrid scan specifies use of approximately the 3.4° (4th lowest) tilt beam to 20 km range, 2.5° to 35 km, 1.5° to 50 km and finally the lowest available 0.5° beam beyond 50 km. The result of these "steps" is often very apparent, especially with shallow storms where the vertical profile of Z_e has maximum values near the ground. Abrupt increases in estimated precipitation are calculated just beyond the ranges where the next-lowest tilt is selected by the PPS hybrid scan, causing a lower portion of the cloud with higher Z_e to be illuminated by the radar.

5.3 Recommendations

It is recommended that Reclamation's SAA be modified for rain and used with NIDS Level III reflectivities. Tests should be conducted to determine how well this approach estimates rainfall as observed by reasonably dense gage networks. Comparisons between the same algorithm's runs with Level II and Level III Z_e observations for heavy rain storms should reveal how much accuracy is lost by using the Level III "degraded" observations. Comparisons of PPS algorithm rain estimates, Reclamation algorithm estimates using Level III data and customization for a particular mountain watershed, both against rainfall measured from a reasonably dense gage network, would also be useful.

6. SUMMARY

- Reclamation is designing EWS to provide enhanced public safety to populations at risk downstream of dam structures during potential flash-flood events.
- The AWARDS system demonstrates a methodology that integrates NEXRAD Level III, Stage III rainfall estimates with modern computer, communication, and Internet technologies for improved water resources management.
- A NEXRAD-enhanced EWS is being developed for the Olympus Dam watershed near Estes Park, CO. This system will integrate the existing EWS stations with NEXRAD Level III, Stage III rainfall estimates and a reliable satellite paging system.
- Using NEXRAD Level III, reflectivity data received from a NIDS vendor, and modifying the Reclamation-developed SAA for rain, has the potential to improve both the spatial and temporal resolutions of the radar rainfall estimates. However, the accumulation resolution of estimated rainfall would be degraded.
- Various options for rain estimation are offered by NIDS products, use of the PPS algorithm, and use of Reclamation's more flexible algorithm. These options involve a number of tradeoffs between spatial, temporal, and accumulation resolutions of rainfall estimates. It is not apparent what the best approach would be for use with Reclamation's EWS.

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